A PRELIMINARY STUDY OF Rb-Sr SYSTEMATICS AND TRACE ELEMENT ABUNDANCES ON IMPACT-MELTED LL-CHONDRITES FROM ANTARCTICA

Osamu OKANO[1], Keiji MISAWA[2], Noboru NAKAMURA[1,2]
Hiroji HONMA[3] and Hiroya GOTO[4]

[1] *Department of Science of Material Differentiation, Graduate School of Science and Technology, Kobe University, 1-1, Rokkodai-cho, Nada-ku, Kobe 657*
[2] *Department of Earth Sciences, Faculty of Science, Kobe University, 1-1, Rokkodai-cho, Nada-ku, Kobe 657*
[3] *Institute for Thermal Spring Research, Okayama University, 827, Yamada, Misasa-cho, Tohaku-gun, Tottori 682-02*
[4] *Laboratory of Geosciences, College of Liberal Arts, Kobe University, 1, Tsurukabuto, Nada-ku, Kobe 657*

Abstract: Rb-Sr systematics, REE, Ba, Sr, Rb, K, Ca and Mg abundances were analyzed in 1) whole-rock samples from 8 Antarctic LL-chondrites including 4 impact-melted rocks and 2 non-Antarctic LL chondrites, and 2) 8 mineral separates from one of the impact-melted meteorites, Y-790964. In a ^{87}Rb-^{87}Sr evolution diagram, analyses from the severely shocked meteorites deviate from the 4.5 b.y.-evolution line although those of normal LL-chondrites are plotted on or close to the line, suggesting a late thermal evolution of these impact-melted meteorites. Analyses of mineral separates and a whole-rock from Y-790964 yield a Rb-Sr internal isochron age of 1197 ± 54 (2σ) m.y. and an initial $^{87}Sr/^{87}Sr$ ratio of 0.73160 ± 0.00028 (2σ). This age is the youngest known among impact-related materials in brecciated meteorites. In addition, the impact-melted meteorites have somewhat higher and fractionated REE, Sr, Rb and K abundances compared with normal LL chondrites.

The 1.2 b.y. age is interpreted as a time of melting induced by intense impacts on the LL-chondrite parent body, accompanied by REE, Rb/Sr and K fractionations. Therefore, we suggest that strong impact and regolith processes on the LL-chondrite parent body never ceased until at least 1.2 b.y. ago.

1. Introduction

SATO *et al.* (1982a) first reported on a series of unique Yamato-79 LL-chondrites, which are characterized by a dark, vesicular, fine-grained and glassy texture, suggesting a related or similar evolutionary history of these meteorites. Major chemical and petrologic features of the meteorites (HARAMURA *et al.*, 1983; SATO *et al.*, 1982b) are similar to those of typical lithic fragments in the brecciated LL-chondrites. The meteorites are, thus, considered to represent a regolith material derived from an LL-chondrite parent body (SATO *et al.*, 1982b).

Recently, brecciated meteorites have attracted the attention of many meteorite workers. As pointed out by KEIL (1982), regolith and impact processes as recorded in the brecciated meteorites as well as early thermal metamorphism are important in understanding the evolutionary history of meteorite parent bodies. In particular, age determination and trace element analyses for shocked lithic stones, like Yamato-79 unusual meteorites, may provide us with important information on the duration and chemical nature of strong impact processes on meteorite parent bodies.

In this article, we present the results of Rb-Sr isotopic studies and analyses of REE and other incompatible trace elements for four Yamato-79 unusual LL-chondrites, Y-790143, -790964, -790519, -790723 and other normal LL-chondrites, Y-74646(LL6–5), -75258(LL6), BTN-78004(LL6), ALH-78109(LL5), Soko Banja (LL4) and Parnallee (LL3). Along with our previous results for the Yamato-790964 chondrite (NAKAMURA and OKANO, 1984), we discuss here their chronological and chemical significance for understanding the regolith and impact processes on the LL-chondrite parent body.

2. Samples and Experimental Procedures

2.1. *Samples*

Among the Yamato-79 unusual LL-chondrites, four specimens (Y-790143, -790964, -790519, -790723) were selected for this study, together with other normal Antarctic (Y-74646, -75258, BTN-78004, ALH-78109) and non-Antarctic (Soko Banja, Parnallee) LL chondrites. Based on chemical compositions of whole rocks and minerals, the former four meteorites are classified as LL-group chondrites (HARAMURA *et al.*, 1983; SATO *et al.*, 1982b). They have a microcrystalline, glassy texture and numerous vesicles similar to some lithic fragments in LL-chondritic breccias. The number of vesicles in these meteorites decreases in the order, Y-790143, -790964, -790519 and -790723 (SATO *et al.*, 1982a; YANAI, 1981); perhaps a rough indication of the degree of shock melting or recrystallization. Following SATO *et al.* (1982a, b), we examined the Y-790964 meteorite petrographically, and identified relic chondrules in some areas and rounded, troilite-like, opaque minerals in metal grains scattered throughout the thin section. Degree of melting and recrystallization seems different from portion to portion in the same meteorite as noted also by SATO *et al.* (1982a). The bulk specimens from the above normal and unusual meteorites were subjected to Rb-Sr isotopic analysis and some of them were analyzed for trace elements.

For internal isochron age determination, mineral separates were obtained from specimen Y-790964, by magnetic separation and 1N-HCl leaching experiment. The results of the meteorite will be presented elsewhere (NAKAMURA and OKANO, 1984). Additional sample descriptions and chemical data are presented in this article. About 1.6 g of meteorite fragments were gently crushed in an agate mortar and then sieved into four size fractions (100–150, 150–200, 200–300 and <300 meshes). After removing metal grains with a hand magnet, each fraction was separated into several fractions using the Frantz Isodynamic Separator and heavy liquids. Purities of minerals in the fractions were estimated by microprobe analyses of Ca, Mg and Fe for 100–300 grains from each fraction (Table 1). It was observed that mineral and glass grains were finely comminuted, so that they were almost impossible to separate completely by the magnetic and density method. Hence, we have applied chemical separation (1N-HCl leaching) to an olivine rich fraction (200–300 mesh) F2-MB, and obtained a leachable fraction (possibly olivine-dissolved) M2-MS and an unleachable residue (glass and pyroxene-rich) M2-MR.

Table 1. Mineral composition estimated from major element data (NAKAMURA and OKANO, 1984) for mineral separates from Yamato-790964.

		Ol*	Opx*	Cpx*	Glass*	Others*
	ϕ<300 mesh					
F1-LM	less magnetic	25	18	35	5	17
F1-M	magnetic	54	11	11	7	17
	300<ϕ<200 mesh					
F2-LM	less magnetic	28	25	37	5	5
F2-MB	magnetic	63	8	11	3	15
F2-MS**	1N-HCl leachable from F2-MB					
F2-MR**	1N-HCl residue from F2-MB	11	37	35	11	6
F2-MM	more magnetic	56	12	10	5	17
FINE	suspension from F1 (<300 mesh)					
F-HL1	heavy liquid separate (3.45<density<3.74 g/cm³)					

*Mineral abundances are given in %.
Ol: olivine, Opx: orthopyroxene, Cpx: clinopyroxene, Others: metal, troilite and glassy or micro-crystalline materials.
**Fractions were obtained by leaching F2-MB fraction with 1N-HCl solution for 80 hours at room temperature.

2.2. Chemical procedures

General analytical procedures employed in this work are presented in Fig. 1. Samples weighing 50 mg for bulk analyses and 15–100 mg for mineral analyses were washed with distilled acetone in an ultrasonic bath prior to the chemical analysis.

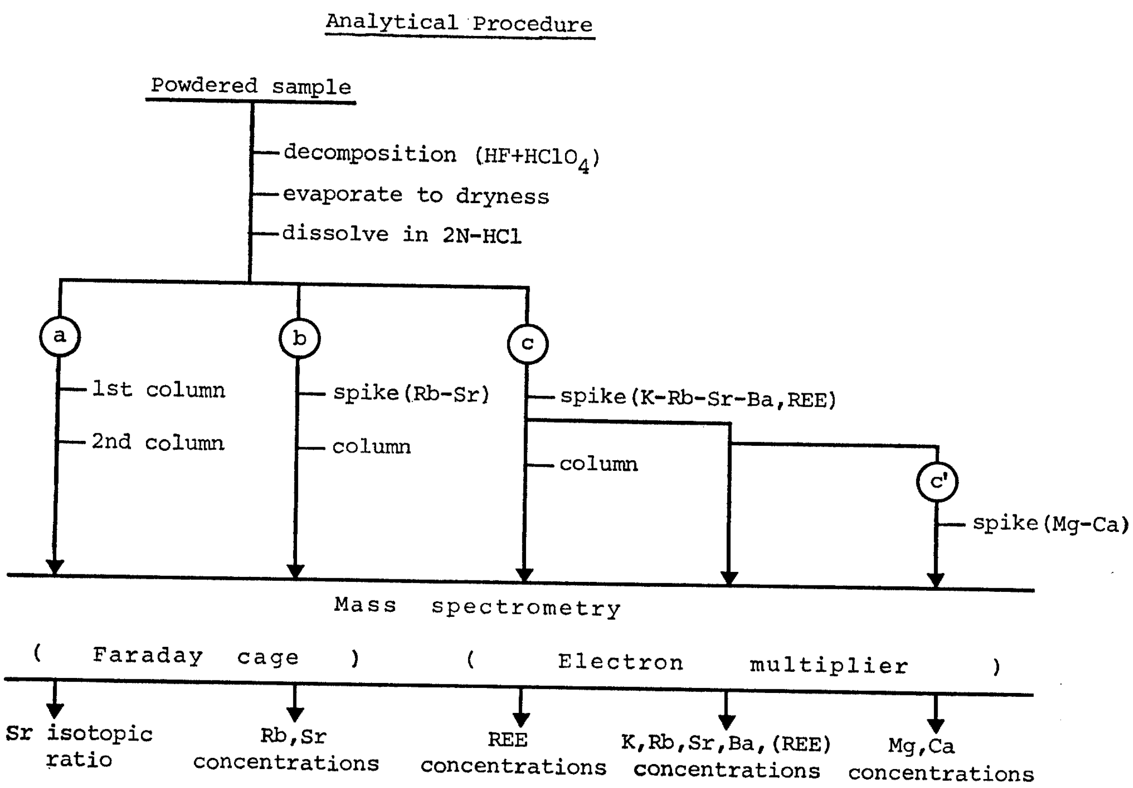

Fig. 1. Schematic diagram of analytical procedures.

Usually, the powdered samples were decomposed with 0.8 g of the HF-$HClO_4$ (1:1) mixture (for 50 mg of sample) in a sealed teflon bomb at 160°C for 8–10 hours in an oven. After complete decomposition and evaporation to dryness on a hot plate, the samples were dissolved in 2–3 m*l* of 2N-HCl in the bomb for several hours at the same temperature to ensure complete dissolution, and then split into three aliquots; one for Sr isotopic composition, another was spiked for precise Rb-Sr concentration determination, and the third was sub-split and spiked for REE, Ba, Sr, Rb and K, and Ca and Mg analyses.

Impurities measured during Rb-Sr chemical analysis and in reagents are given in Table 2. Blank effects on Rb and Sr analyses are nearly negligible (less than 0.2%), except for fraction F2-MS, 1.5% for concentration and 1% for Sr isotopic composition. All data in Table 5 were corrected for blank.

Table 2. Rb and Sr blanks in reagents (10^{-9} g/g) and for whole chemical procedures (10^{-9} g).

Reagents		Rb	Sr
H_2O		0.00022	0.00034
HF		0.0055	0.021
$HClO_4$		0.0031	0.018
2N-HCl*	No. 1**	0.00086	0.0057
	No. 2**	0.00054	0.0059
12N-HCl*		0.0015	0.01
Whole procedure (10^{-9} g)***			
A		0.020	0.08
B		0.015	0.071
C		—	0.18

*HF, $HClO_4$ and 2N-HCl (No. 1) were purified by four-fold sub-boiling of commercial special grade reagents. 12N-HCl was made from HCl gas and diluted to 2N-HCl (No. 2).

**2N-HCl (No. 1) was used for whole rock samples of Soko Banja, Y-74646, -75258, -790143, -790519 and -790964, and F1-LM and F1-M fractions from Y-790964. No. 2 was used for other samples.

***A and B represent whole chemical procedures for analyses of Rb and Sr abundances (B is the case for F2-MS sample from Y-790964), and C for Sr isotopic analyses.

Isotopic dilution analyses of trace elements, Ca and Mg were carried out at Kobe University using a mass spectrometer, Model JEOL MS5. Including blank correction, precisions of trace element concentrations are considered to be normally better than 2% (possibly up to 5%). Since the sub-split for Ca and Mg analyses was taken volumetrically by a micro pipet, concentrations of Ca and Mg in most samples (except for Y-790964) include large errors (~10%).

2.3. *Isotopic analyses for Rb-Sr systematics*

The concentration aliquot was spiked with ^{87}Rb-^{84}Sr mixed tracer solution. The isotopic ratios, $^{87}Rb/^{85}Rb$ for Rb concentration, and $^{84}Sr/^{86}Sr$ and $^{84}Sr/^{88}Sr$ for Sr concentration, were measured and corrected for mass discriminations based on measurements of Rb and Sr standards. The Sr concentrations calculated from both ratios normally agree within 0.1%. Mass spectrometric errors in Rb concentrations are estimated to be 0.3%, although larger errors up to 1% are possible for the fraction F2-MS. Considering errors in weighing, tracer calibration and mass discrimination, errors in Rb and Sr concentrations are estimated to be 1%. Our present precisions of $^{87}Rb/^{86}Sr$ ratios for 10 mg of chondritic specimens are believed to be better than 0.8%.

All the isotopic measurements for Rb-Sr systematics were carried out at Okayama University using a computer controlled, automatic on-line mass spectrometer Model MAT-261. The $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr=0.1194$ and those for the NBS 987 Sr standard obtained during the course of this work are given in Table 3. The mean ratio of 0.71021 ± 0.00002 (2σ) agrees with our previous value (NAKAMURA *et al.*, 1982) and with those obtained within the last 2–3 years by this machine (KAGAMI *et al.*, 1982). The Sr mass spectrometry employed in this work is similar to that of NAKAMURA *et al.* (1976). For each sample, normally 2–3 runs were performed and 180–270 ratios of $^{87}Sr/^{86}Sr$ were collected. Typically, $^{87}Sr/^{86}Sr$ ratios vary 3–4 in the 5th decimal place (95% confidence level) for 50 ng of Sr.

Table 3. $^{87}Sr/^{86}Sr$ for NBS 987 Sr standard.

Date	Sr (10^{-9} g)	No. of blocks*	$^{87}Sr/^{86}Sr$**
Sep. 5, 1983	20	20	0.71022 (8)
Oct. 9	50	10	0.71019 (10)
Oct. 10	13	10	0.71025 (10)
Feb. 4, 1984	100	10	0.71032 (8)
Mar. 10	50	20	0.71020 (7)
May 3	50	20	0.71021 (2)
Sep. 8	50	20	0.71022 (8)
Sep. 9	50	20	0.71021 (2)
Sep. 22	50	20	0.71021 (3)
Oct. 6	50	20	0.71020 (3)
		Mean	0.71021 (2)

*Each block contains 9 isotopic ratios.
**$^{87}Sr/^{86}Sr$ ratios are normalized to $^{86}Sr/^{88}Sr=0.1194$. Errors correspond to the last digits and are the 95% confidence level (C.L.) for the means.

3. Results and Discussion

3.1. *Trace element abundances in bulk meteorites*

Although Ca and Mg data in this work are of low quality in general, the Ca and Mg concentrations in the Y-74646 and -75258 meteorites are significantly higher than those of HARAMURA *et al.* (1983) and those of normal LL-chondrites (MASON, 1971a, b), suggesting a reflection of local chemical heterogeneities of specimens analyzed in this work.

From the previous works (GOLES, 1971a, b; MINSTER and ALLÈGRE, 1981; WLOTZKA *et al.*, 1983), it is found that abundances of alkali metals (Rb and K) in LL-chondrites vary from chondrite to chondrite and portion to portion, even in the same chondrite. Our data of Rb and K (Table 4) show similar results. Moreover, it is worth pointing out that three of the most recrystallized chondrites (Y-790143, -790964 and -790519) have the highest K and Rb values compared with other normal LL-chondrites. This feature may be ascribed to the presence of glassy material suggested from petrological observations and leaching experiments of these specimens which could be enriched in incompatible elements.

Table 4. Elemental abundances in bulk LL-chondrites. Concentrations are given in ppm unless otherwise noted.

Element	Soko Banja*	Y-74646	Y-75258*	Y-790143	Y-790519
Mg (%)	15.7	19.3	18.9	—	—
Ca (%)	1.30	1.73	1.70	—	—
K	285	745	585	967	1084
Rb	0.619	2.56	1.05	5.42	3.80
Sr	10.27	10.88	10.68	12.37	10.82
Ba	3.00	3.62	3.59	4.90	4.77
La	0.307	0.326	0.300	0.393	0.37
Ce	0.919	0.888	—	0.960	0.947
Nd	0.649	0.650	0.592	0.676	0.724
Sm	0.199	0.212	—	0.214	0.225
Eu	0.0755	0.0873	0.0844	0.0841	0.0825
Gd	0.278	0.295	0.248	0.286	0.303
Dy	0.320	0.339	0.341	0.335	0.353
Er	0.212	0.228	0.232	0.228	0.237
Yb	—	—	0.250	—	—
Lu	—	0.0364	—	0.0382	0.0379

*Abundances were determined by direct-loading mass spectrometry.

In Fig. 2, trace element patterns for the normal and the unusual LL-chondrites are shown. It is interesting that although all the LL-chondrites analyzed here show generally flat REE patterns with some variations in absolute abundances, the three most recrystallized chondrites have somewhat higher LREE abundances, paralleling the high K, Rb and Sr values. As noted by NAKAMURA and OKANO (1984), REE of the Y-790964 meteorite are slightly fractionated compared with normal LL-chondrites. Although such a trace element feature may partly be a reflection of sampling effects, it seems probable that the presence of significant amounts of glass and euhedral clinopyroxene with chemical zoning (SATO *et al.*, 1982b) may be responsible for the observed trace element enrichment and some fractionations.

As reported by SATO *et al.* (1982a, b) and checked partly by us, a thin section of specimen Y-790964 shows euhedral chemically zoned pyroxene crystals ($En_{69}Fs_{24}Wo_{7}$ at the core, $En_{47}Fs_{15}Wo_{38}$ at the rim) embedded in an extremely comminuted and vitreous matrix with small euhedral olivine crystals. In some areas, relic chondrules and rounded troilite minerals within metal grains were noted. Therefore, we suggest that these meteorites were once heated beyond the melting point (950°C) of metal/troilite, reaching melting points of silicate minerals (1200–1400°C) for a short time. Partial melting and/or total melting ensued locally, followed by rather rapid crystallization with minor chemical fractionations before squeezing out troilite and metal from bulk meteorites (SMITH and GOLDSTEIN, 1977).

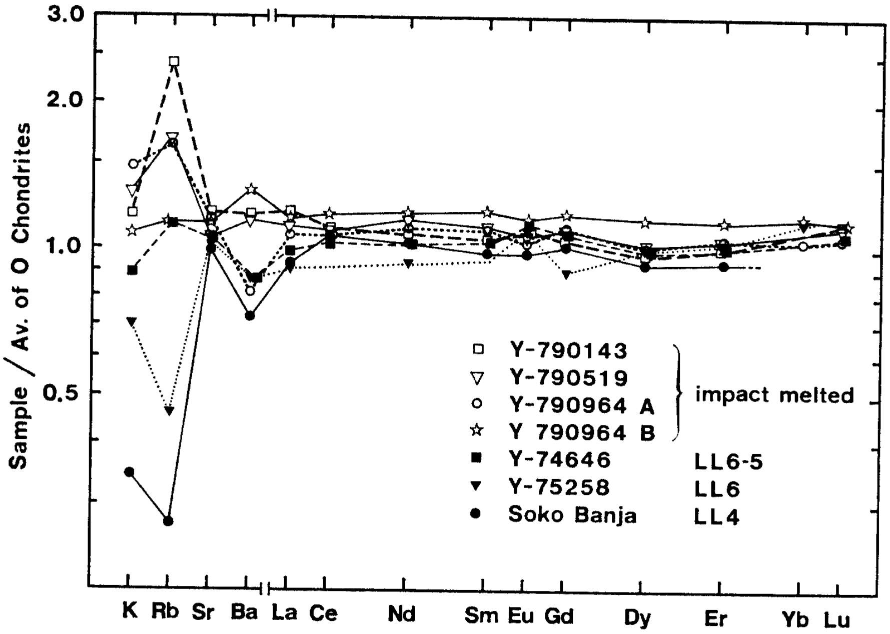

Fig. 2. Trace element abundance patterns for the normal and the impact-melted LL-chondrites. Abundances are normalized to average of 10 ordinary chondrites for REE and Ba (NAKAMURA, 1974) or to the most frequently observed values of K, Rb and Sr (NAKAMURA and OKANO, 1984).

3.2. Rb-Sr systematics of bulk meteorites

The results of Rb-Sr isotopic analyses for bulk meteorites are presented in Table 5 and Fig. 3. The variations of Rb and Sr concentrations and of $^{87}Rb/^{86}Sr$ ratios obtained for Antarctic and non-Antarctic meteorites in this work are within the range of other non-Antarctic LL-chondrites reported by MINSTER and ALLÈGRE (1981) and by GOPALAN and WETHERILL (1969). However, the $^{87}Rb/^{86}Sr$ ratios of three unusual meteorites (Y-790964, -790143, -790519) are highest among LL-chondrites.

Table 5. Results of Rb-Sr analyses for whole rocks of LL-chondrites.

Sample	Type	Weight (mg)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$*	$^{87}Sr/^{86}Sr$**	Model age*** (b.y.)
Parnallee	LL3	47.4	2.801	10.53	0.773	0.74936 (4)	4.46
Soko Banja	LL4	48.6	0.618	10.27	0.1742	0.71099 (3)	4.75
Y-74646	LL6–5	49.6	2.564	10.88	0.684	0.74483 (4)	4.58
Y-75258	LL6	49.1	1.045	10.68	0.2837	0.71781 (6)	4.56
ALH-78109	LL5	50.3	2.692	12.63	0.618	0.73812 (4)	4.34
BTN-78004	LL6	49.3	2.491	11.18	0.647	0.74068 (3)	4.41
Y-790143	impact-melted	52.6	5.415	12.37	1.277	0.79483 (3)	5.10
Y-790519	impact-melted	49.0	3.800	10.82	1.021	0.75446 (3)	3.74
Y-790723	impact-melted	45.6	0.722	10.20	0.2048	0.71211 (2)	4.42
Y-790964 A	impact-melted	52.0	3.666	12.08	0.882	0.74721 (13)	3.76

*Errors are less than 0.8%.

**Ratios are normalized to $^{86}Sr/^{88}Sr=0.1194$. Errors correspond to the last digits and 95% C.L.

***Model ages are calculated using the bias-adjusted Allende initial $^{87}Sr/^{86}Sr=0.69884$ (GRAY *et al.*, 1973).

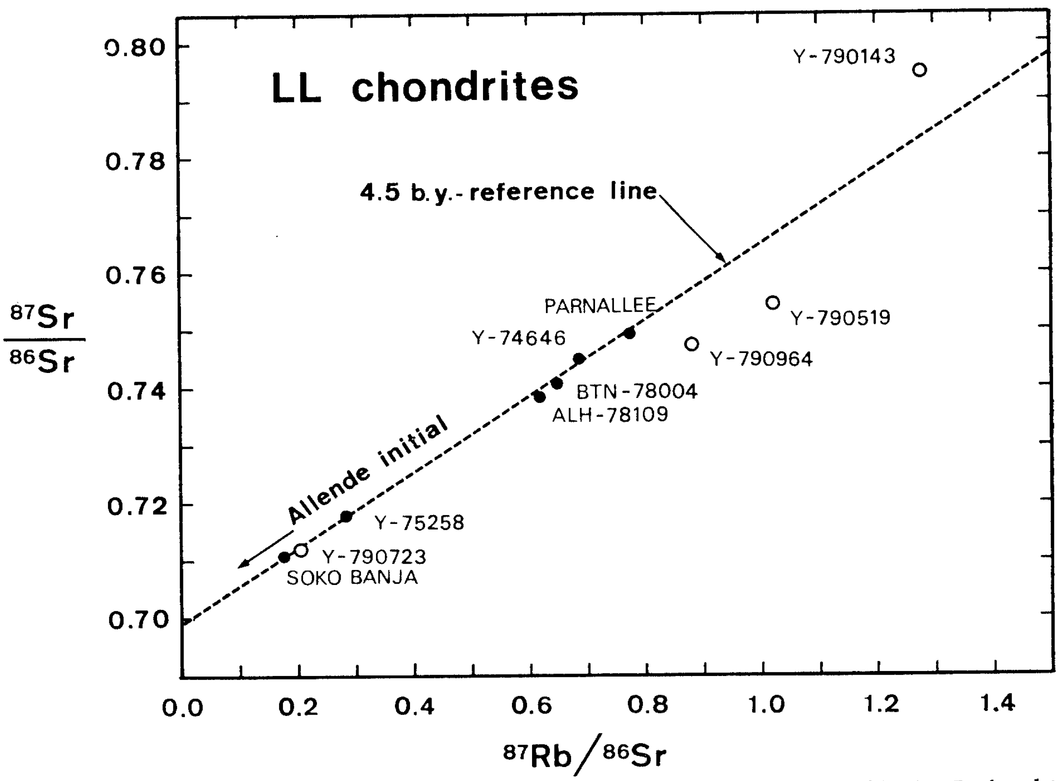

Fig. 3. The ^{87}Rb-^{87}Sr evolution diagram for the normal (●) and the impact-melted (○) LL-chondrites. Note that all the data points of normal LL-chondrites are on or close to the 4.5 b.y. evolution line, but not the impact-melted ones.

The model ages calculated for the bulk meteorites using the initial $^{87}Sr/^{86}Sr$ ratio of Allende meteorite (ALL) (bias-adjusted value=0.69884; GRAY *et al.*, 1973) range from 4.34 to 4.75 b.y. for normal LL-chondrites (Table 5) with typical errors of 0.04 b.y. This range for model ages appears to be larger than those of MINSTER and ALLÈGRE (1981). Although our samples appear to be fresh under the microscope, it may be possible that the variations are partly due to weathering effects while buried in the Antarctic ice. Other possible reasons include later Rb-Sr system disturbances by impacts on the parent body, or experimental artifacts in the laboratory. In order to clarify these problems, further analyses of non-Antarctic falls may be helpful.

In any case, compared with shocked meteorites, these variations for normal chondrites are still minor. As shown in a ^{87}Rb-^{87}Sr evolution diagram (Fig. 3), data points for normal LL chondrites are on or close to the 4.5 b.y.-age evolution line. However, data points of the three unusual LL-chondrites are far away from the line. Including the specimen Y-790723, these meteorite specimens were sampled from the interior parts of the original stones (YANAI, 1983, written communications) and thus may represent least-weathered portions of the meteorites. Moreover, these meteorites show some similar trace element fractionations to normal ones, despite the Rb-Sr isotopic variations. Therefore, we consider that the Rb-Sr system of these three unusual meteorites was reset or partly reset by some young thermal event(s). In view of trace element chemical features, as mentioned in the previous section, and the petrological characteristics of the meteorites, the thermal event must have been an igneous or intense metamorphic one leading to total melting locally or partial melting, possibly triggered by intensive impacts.

3.3. *1.2 b.y. impact-melting age and trace element fractionation recorded in the Yamato-790964 meteorite*

In order to clarify age and trace element characteristics for the reheating episode recorded in the bulk specimens of Yamato-79 unusual meteorites, we have carried out Rb-Sr isotopic and trace element analyses for some mineral separates from one of them, Y-790964.

Trace element results are given in Table 6 and Fig. 4. In Fig. 4, the pyroxene-rich fraction (F1-LM) shows the most fractionated REE pattern with a small negative Eu anomaly and gradual increase from lighter REE to heavier REE, paralleling the de-

Table 6. Elemental abundances in mineral separates and whole rocks from Y-790964. Abundances are given in ppm unless otherwise noted.

Element	F1-LM*	F1-M*	WR-A**	WR-B**
Mg (%)	17.5	19.1	14.4	15.7
Ca (%)	3.53	1.57	1.55	1.44
K	525	1139	1220	890
Rb	1.52	3.48	3.67	2.56
Sr	10.10	11.19	12.08	11.82
Ba	3.58	4.06	3.35	5.45
La	0.329	0.378	0.349	0.378
Ce	—	—	0.923	1.02
Nd	0.700	0.716	0.695	0.753
Sm	0.249	0.235	0.223	0.243
Eu	0.0846	0.0879	0.0794	0.0883
Gd	0.363	0.309	0.306	0.326
Dy	0.462	0.364	0.346	0.396
Er	0.313	0.235	0.236	0.257
Yb	—	—	0.228	0.257
Lu	0.0403	—	0.0359	0.0390

*Abundances were determined by direct-loading mass spectrometry.
**After NAKAMURA and OKANO (1984).

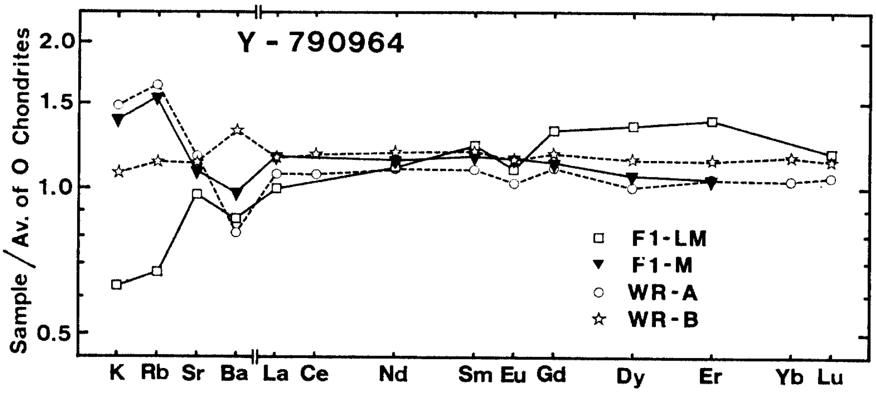

Fig. 4. Trace element abundance patterns for mineral separates and whole rocks from Y-790964 impact-melted LL-chondrite.

pletions of K and Rb. However, the fractionation is not so pronounced compared with typical clinopyroxenes in achondrites (NAKAMURA *et al.*, 1983) or in equilibrated ordinary chondrites (CURTIS and SCHMITT, 1979). On the other hand, the F1-M fraction which was supposed to be rather enriched in olivine shows almost no fractionation from the whole rock with respect to the trace element abundances. Since solid/liquid partition coefficients of these incompatible trace elements for olivine are so small (SCHNETZLER and PHILOPOTTS, 1970), it is possible that the typical REE pattern of olivine could be cancelled out by the presence of minor incompatible element-rich components such as glass or phosphate even if this fraction contains significant amounts ($\sim$50%) of olivine.

Results of Rb-Sr isotopic analyses have been presented in NAKAMURA and OKANO (1984). We discuss them here mainly in relation to trace element behaviors and general age significances for other similar meteorites in question.

In Fig. 5 is shown the ^{87}Rb-^{87}Sr evolution diagram for the Y-790964 meteorite. Among 9 (mineral and bulk) specimens analyzed, two fractions (F1-M, F2-MS) and a

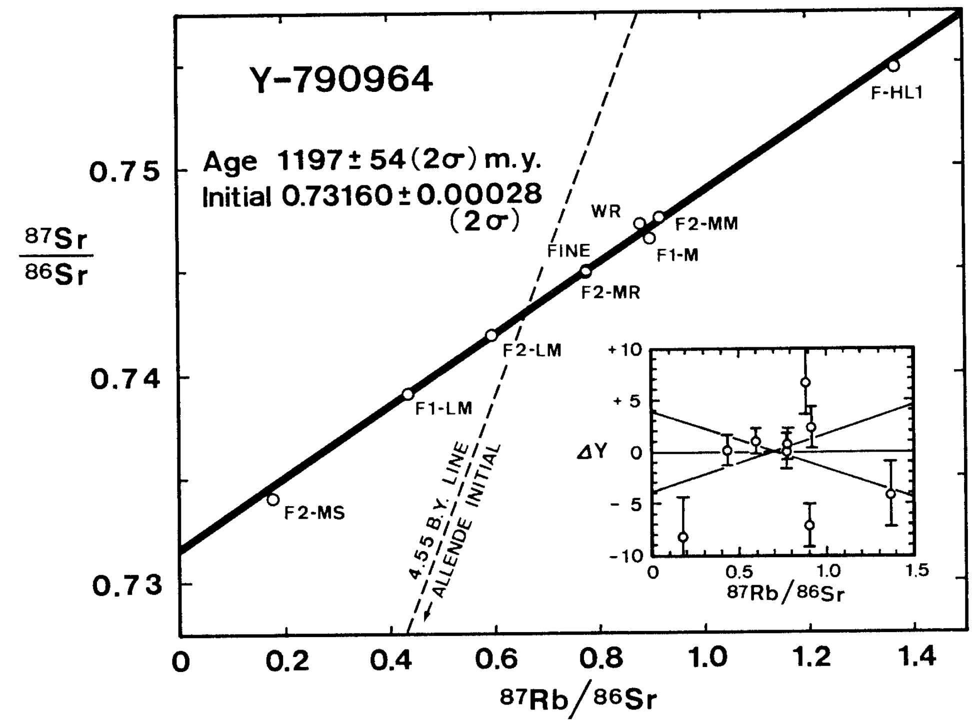

Fig. 5. The ^{87}Rb-^{87}Sr internal isochron diagram for Y-790964 meteorite (NAKAMURA and OKANO, 1984).

whole rock show minor deviation from the general trend. Hence, it is possible that the Rb-Sr system of them was not completely reset by an event and not in equilibrium with others. Such a minor inconsistency of the Rb-Sr system may be understandable in view of the presence of relic chondrules in the meteorite. Since the deviations of them from the regression line are rather small, it is believed that the small trace element fractionation mentioned above is partly due to the lack of equilibrium partitioning of trace elements (*e.g.* incomplete development of crystals).

It is worth noting that the five data points in Fig. 5 are perfectly on the regression line within the experimental errors. Including all mineral and whole rock data, an age of 1197±54 (2σ) m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.73160±0.00028 (2σ) are calculated from the line, indicating the youngest episode of melting and Rb/Sr fractionation on the LL chondrite parent body (NAKAMURA and OKANO, 1984). From the general similarity of trace element abundances and petrological features of the other three unusual LL-chondrites to those of the Y-790964 meteorite, it is highly possible that the 1.2 b.y. melting event deduced from examinations of Y-790964 is also responsible for the Rb-Sr isotopic resetting and establishment of chemical and petrological features observed for other three chondrites in question. If this is the case, we can expect a whole rock isochron for these meteorites. It turned out that the Rb-Sr data points of three meteorites (Y-790964, -790519, -790723) showed a linear array corresponding to 3.7 b.y. in age but data points of Y-790143 and another "whole rock" sample (WR-B) from Y-790964 (NAKAMURA and OKANO, 1984) were far away from the linear trend. Therefore, it is suggested that the event(s) responsible for the deviation of Rb-Sr isotopic systems from the 4.5 b.y. evolution line (Fig. 3) was not severe enough to enable the systems complete Rb-Sr isotopic equilibration in all four of the meteorites but strong enough to nearly equilibrate the system within the small scale area (mm-size).

Among many impact-related meteoritic materials, the 1.2 b.y. age for the Y-790964 meteorite is, so far as we know, the youngest, and, therefore, is important for determining duration of strong impact processes on the LL-chondrite parent body. It is interesting that the 1.2 b.y. age obtained here is rather similar to the 1.36 b.y. K-Ar age of H-group clast in the St. Mesmin LL-chondrite (SCHULTZ and SIGNER, 1977). Since the age data for impact-related material of meteorites, particularly by the Rb-Sr method or other ones such as Sm-Nd and U-Th-Pb methods, are still rare, our success with a Rb-Sr internal isochron age determination for impact-melted meteorites should encourage further chronological works on impact-related meteorite materials in brecciated meteorites.

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References

CURTIS, D. B. and SCHMITT, R. A. (1979): The petrogenesis of L-6 chondrites; Insights from the chemistry of minerals. Geochim. Cosmochim. Acta, **43**, 1091–1103.

GOLES, G. G. (1971a): Potassium. Handbook of Elemental Abundances in Meteorites, ed. by B. MASON. New York, Gordon and Breach, 149–169.

GOLES, G. G. (1971b): Rubidium. Handbook of Elemental Abundances in Meteorites, ed. by B. MASON. New York, Gordon and Breach, 285–296.

GOPALAN, K. and WETHERILL, G. W. (1969): Rubidium-Strontium age of amphoterite (LL) chondrites. J. Geophys. Res., **74**, 4349–4358.

GRAY, C. M., PAPANASTASSIOU, D. A. and WASSERBURG, G. J. (1973): The identification of early condensates from the solar nebula. Icarus, **20**, 213–239.

HARAMURA, H., KUSHIRO, I. and YANAI, K. (1983): Chemical compositions of Antarctic meteorites I. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 109–121.

KAGAMI, H., OKANO, O., SUDO, H. and HONMA, H. (1982): Isotopic analysis of Rb and Sr using a full automatic thermal ionization mass spectrometer. Pap. Inst. Therm. Spring Res., Okayama Univ., **52**, 51–70.

KEIL, K. (1982): Composition and origin of chondritic breccias. Workshop on Lunar Breccias and Soils and Their Meteorite Analogs, ed. by G. J. TAYLOR and L. L. WILKENING. Houston, Lunar Planet. Inst., 65–83 (LPI Tech. Rep. 82–02).

MASON, B. (1971a): Calcium. Handbook of Elemental Abundances in Meteorites, ed. by B. MASON. New York, Gordon and Breach, 171–173.

MASON, B. (1971b): Magnesium. Handbook of Elemental Abundances in Meteorites, ed. by B. MASON. New York, Gordon and Breach, 115–119.

MINSTER, J. F. and ALLÈGRE, C. J. (1981): ^{87}Rb-^{87}Sr dating of LL chondrites. Earth Planet. Sci. Lett., **56**, 89–106.

NAKAMURA, N. (1974): Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. Geochim. Cosmochim. Acta, **38**, 757–775.

NAKAMURA, N. and OKANO, O. (1984): A 1.2 b.y. impact-melting age and trace element chemical features of the Yamato-790964 LL chondrite. submitted to Nature.

NAKAMURA, N., TATSUMOTO, M., NUNES, P. D., UNRUH, D. M., SCHWAB, A. P. and WILDEMAN, T. T. (1976): 4.4 b.y.-old clast in Boulder 7, Apollo 17; A comprehensive chronological study of U-Pb, Rb-Sr and Sm-Nd methods. Proc. Lunar Sci. Conf., 7th, 2309–2333.

NAKAMURA, N., KAGAMI, H. and KOMI, H. (1982): Origin of the Chassigny achondrite; Evidence from Rb-Sr isotopic systematics and REE abundances. Abstracts 5th Inter. Conf. Geochronol. Cosmochronol. Isotope Geol., 263–264.

NAKAMURA, N., TATSUMOTO, M. and COFFRANT, D. (1983): Sm-Nd isotopic systematics and REE abundance studies of the ALH-765 eucrite. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 323–331.

SATO, G., TAKEDA, H., YANAI, K. and KOJIMA, H. (1982a): Impact-melted LL-chondrites of Yamato-79 collection. Papers presented to the Seventh symposium on Antarctic Meteorites, 19–20 February 1983. Tokyo, Natl Inst. Polar Res., 9–10.

SATO, G., TAKEDA, H., YANAI, K. and KOJIMA, H. (1982b): Electron microprobe study of impact-melted regolith breccias. Workshop on Lunar Breccias and Soils and Their Meteorite Analogs, ed. by G. J. TAYLOR and L. L. WILKENING. Houston, Lunar Planet. Inst., 120–122 (LPI Tech. Rep. 82–02).

SCHNETZLER, C. C. and PHILPOTTS, J. A. (1970): Partition coefficients of rare-earth elements between igneous matrix material and rock-forming mineral phenocrysts-II. Geochim. Cosmochim. Acta, **34**, 331–340.

SCHULTZ, L. and SIGNER, P. (1977): Noble gases in the St. Mesmin chondrite; Implications to the irradiation history of a brecciated meteorite. Earth Planet. Sci. Lett., **36**, 363–371.

SHIMA, M. and HONDA, M. (1967): Determination of rubidium-strontium age of chondrites using their separated components. Earth Planet. Sci. Lett., **2**, 337–343.

SMITH, B. A. and GOLDSTEIN, J. I. (1977): The metallic microstructures and thermal histories of severely reheated chondrites. Geochim. Cosmochim. Acta, **41**, 1061–1072.

WLOTZKA, F., PALME, H., SPETTEL, B., WANKE, H., FREDRIKSSON, K. and NOONAN, A. F. (1983): Alkali differentiation in LL-chondrites. Geochim. Cosmochim. Acta, **47**, 743–757.

YANAI, K., comp. (1981): Photographic Catalog of the Selected Antarctic Meteorites in the Collection of National Institute of Polar Research. 1st ed. Tokyo, Natl Inst. Polar Res., 104 p.

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